National Aeronautics and Space Administration

Solar Electric Propulsion

In Space Propulsion Technology Project
NASA Marshall Space Flight Center
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Earth Science Technology Conference 2006
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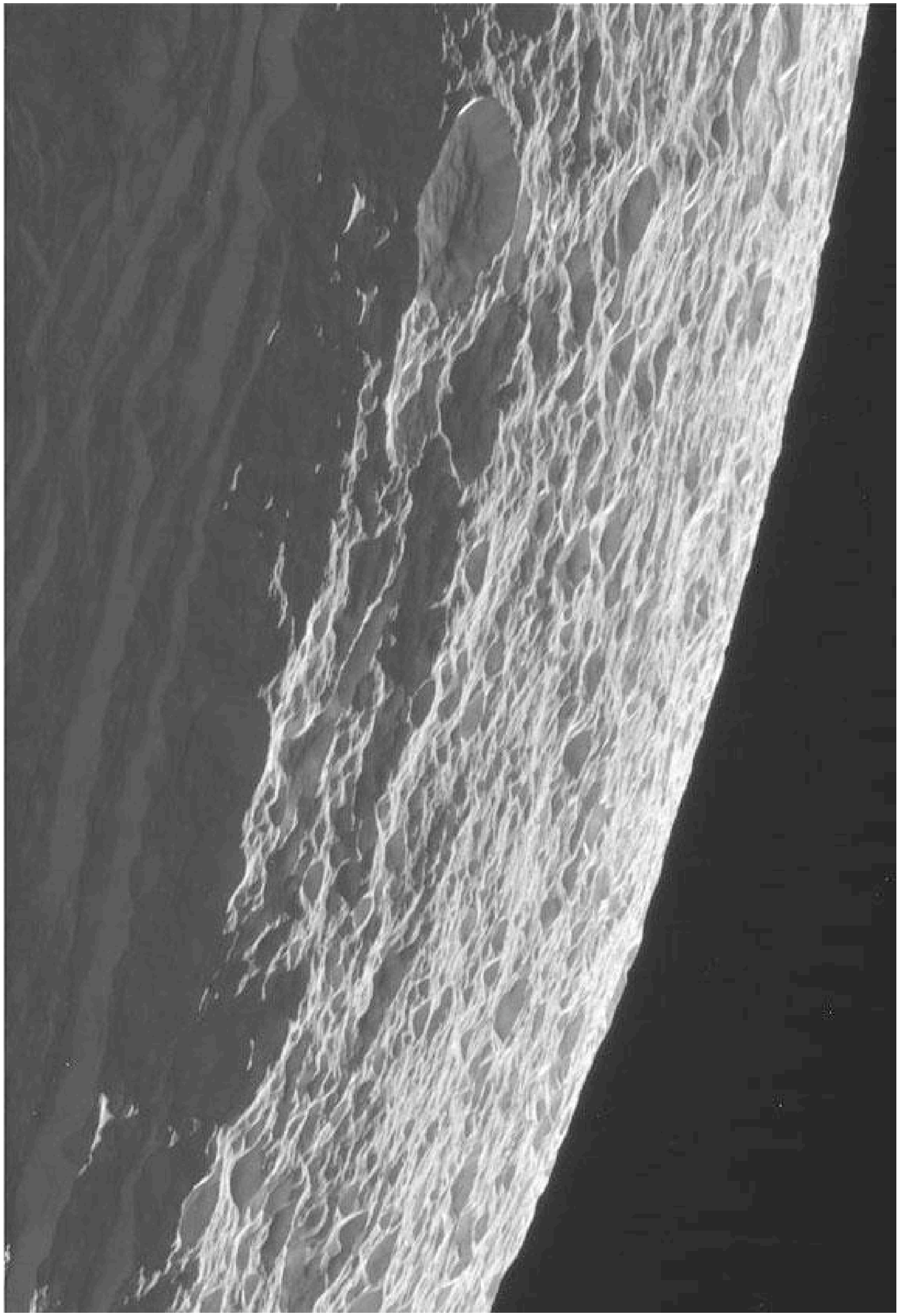


Outline

- Background: Why the Interest in Solar Electric Propulsion?
- Types of Electric Thrusters: a Quick Review
- Primary In-Space Propulsion Program SEP Task Areas
- Future Directions

Background

<u>Chemical propulsion</u> converts the energy stored in the molecular bonds of a propellant into kinetic energy

- Typically high thrust to weight (required for launch)
- <u>But</u> the exhaust velocity is limited by the chemical energy available
- Why is this important?

$$\frac{M_f}{M_0} = \exp\left[-\Delta V / v_e \right]$$

- For a given change in velocity (ΔV), the delivered mass (M_f) depends on the propellant exhaust velocity (v_e)
- More propellant is required to provide a given impulse at lower exhaust velocities

Background

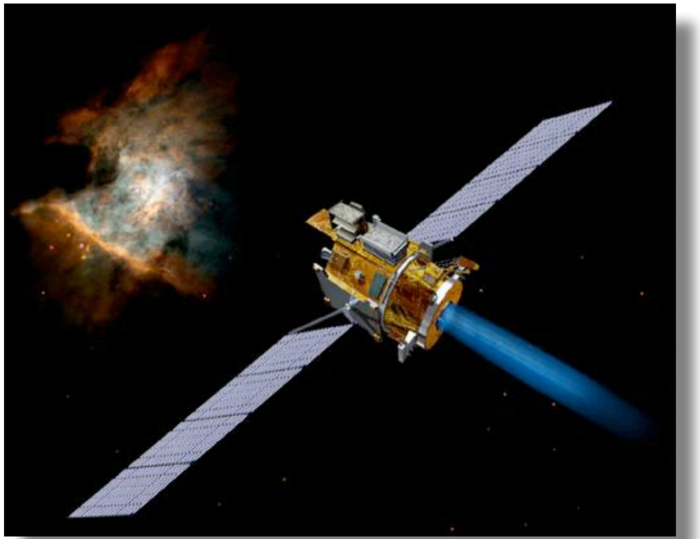
<u>Electric propulsion</u> (EP) uses electrical power to provide kinetic energy to a gas propellant

- Decouples kinetic energy from limitations of chemical energy
- Provides higher exhaust velocities than chemical engines
  - Reduces propellant mass needed to provide a given impulse
  - Allows reduction in launch mass <u>or</u> increase in payload; can provide substantial benefits in mission cost
- Electric propulsion primarily benefits large total impulse missions
  - Orbit raising, repositioning, long-term station keeping
  - Robotic planetary and deep space science missions
  - Precise impulse bits for formation flying (pulsed EP systems)
- Electric propulsion employed on over 180 spacecraft, including EO-1 (earth observation), SMART-1 (lunar mission), and DS-1 (comet fly-by), with DAWN (asteroid mission) to launch in 2007

Background

Additional considerations…

- Lower thrust to weight than chemical engines
    - Small but steady acceleration, vs. short-burn chemical engines
    - EP engines must be designed for long life (thousands of hours)



- Increased dry mass due to:
    - Solar arrays
    - Power processing unit
    - Other EP specific hardware
- Spacecraft integration considerations:
    - Electric power requirements
    - Plasma plume and potential EMI
- Propulsion system trades performed to evaluate whether a given mission will benefit from the use of electric propulsion

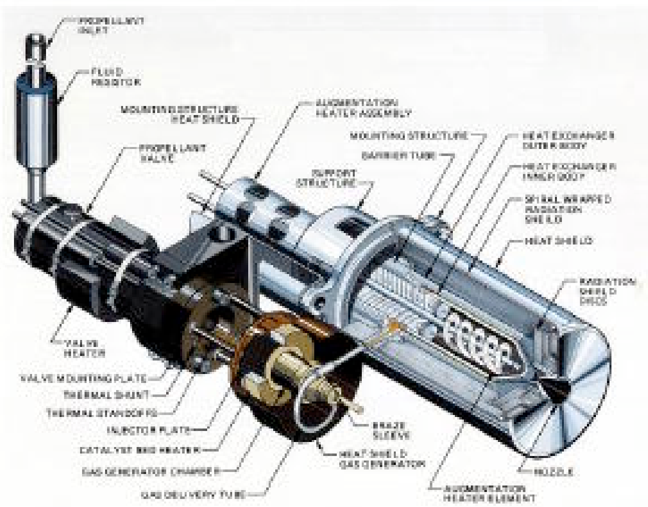
Electric Propulsion

Electric thrusters are generally categorized by their primary acceleration mechanism:

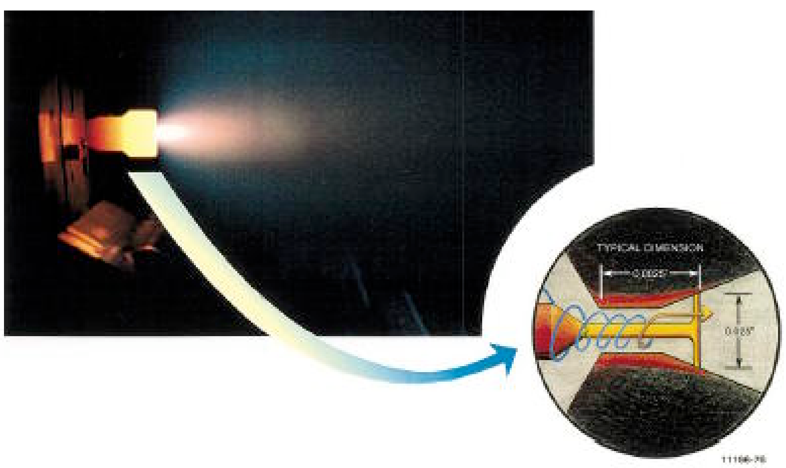
- Electrothermal
  - Resistojet (commercial flight units available)
  - Arcjet (commercial flight units available)
- Electrostatic
  - Hall effect thrusters (commercial flight units + development)
  - Gridded ion thrusters (commercial flight units + development)
- Electromagnetic
  - Pulsed plasma thruster (commercial flight units available)
  - Magnetoplasmadynamic thruster (laboratory models only)
  - Pulsed inductive thruster (laboratory models only)

Electrothermal Thrusters

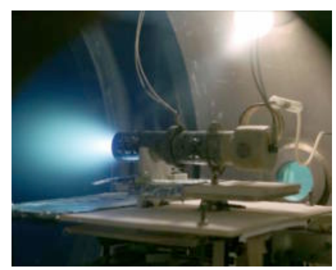
- heat gas and expand through a nozzle



<u>Resistojet</u> thrusters use resistive heating elements to increase the thermal energy of a gas propellant

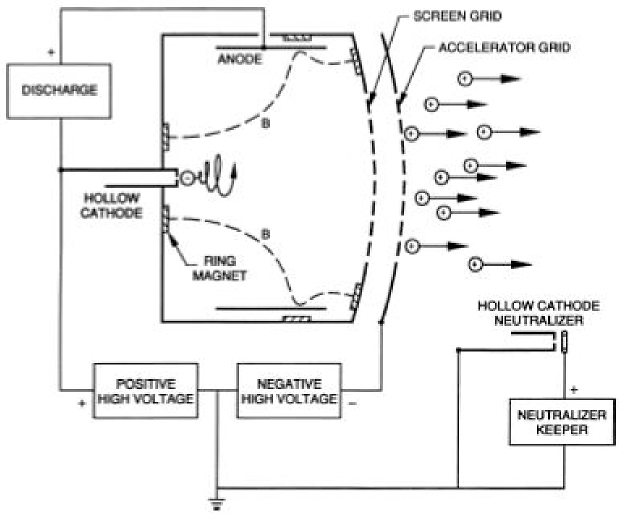


<u>Arcjet</u> thrusters use an electric arc to increase the thermal energy of a gas propellant

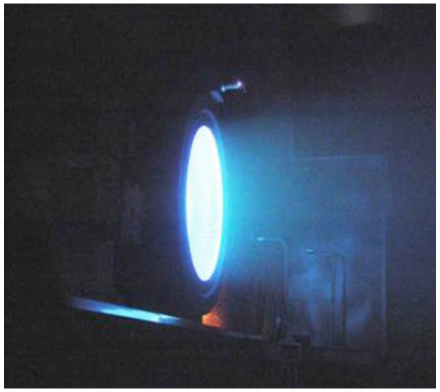


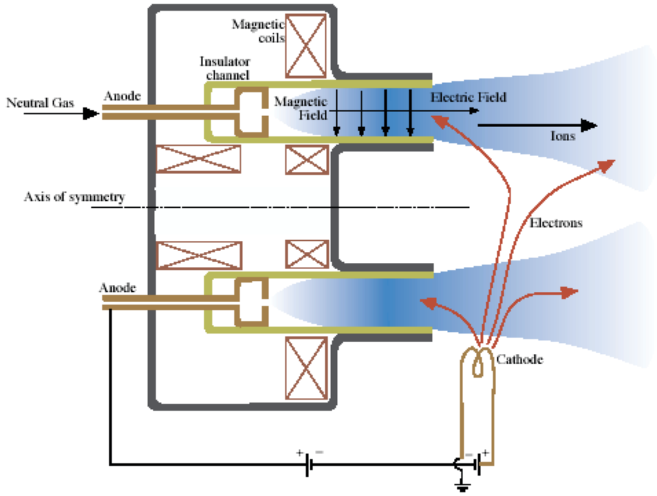
Electrostatic Thrusters

- generate high voltages for ion (plasma) acceleration

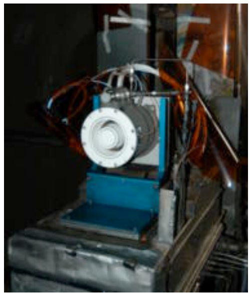


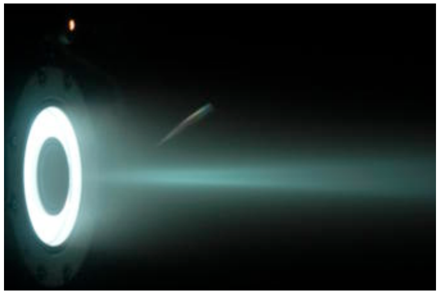
<u>Ion</u> thrusters use closely spaced high voltage grids to create an electrostatic field





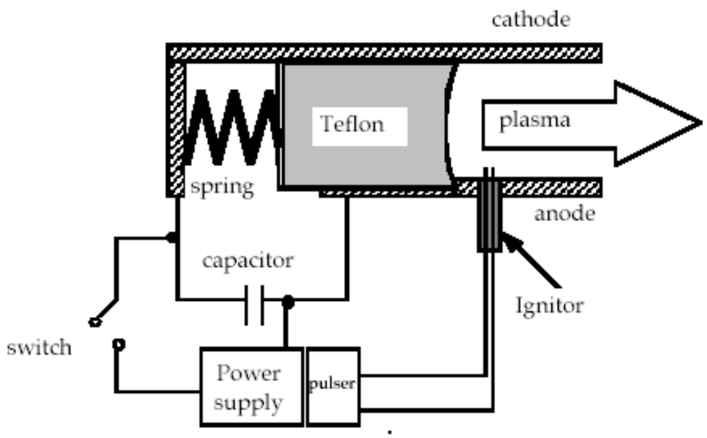
<u>Hall</u> thrusters use magnetically trapped electrons to create an electrostatic field



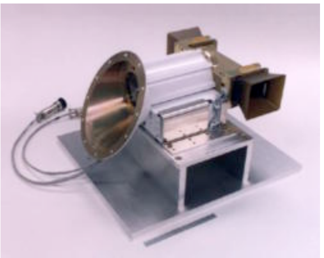


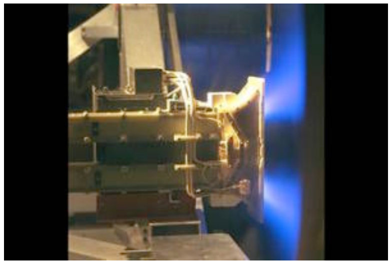
Electromagnetic Thrusters

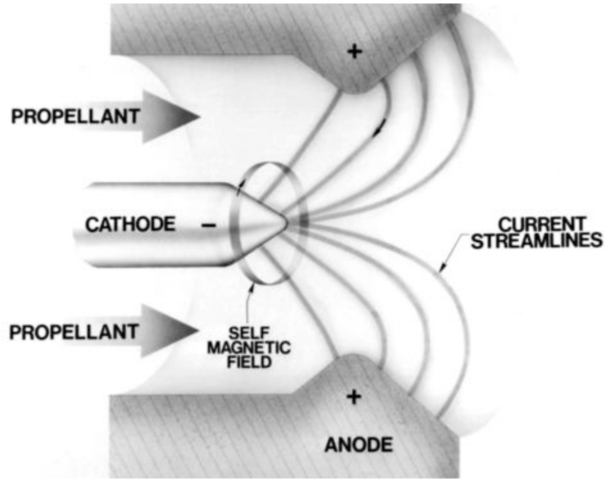
- apply a Lorentz (JxB) force for plasma acceleration



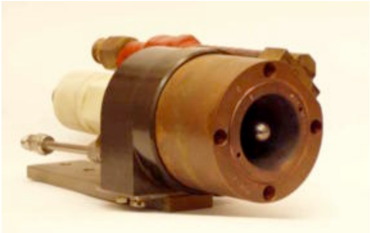
<u>Pulsed Plasma</u> thrusters use a pulsed, repetitive current to ablate solid propellant, induce magnetic field (JxB)



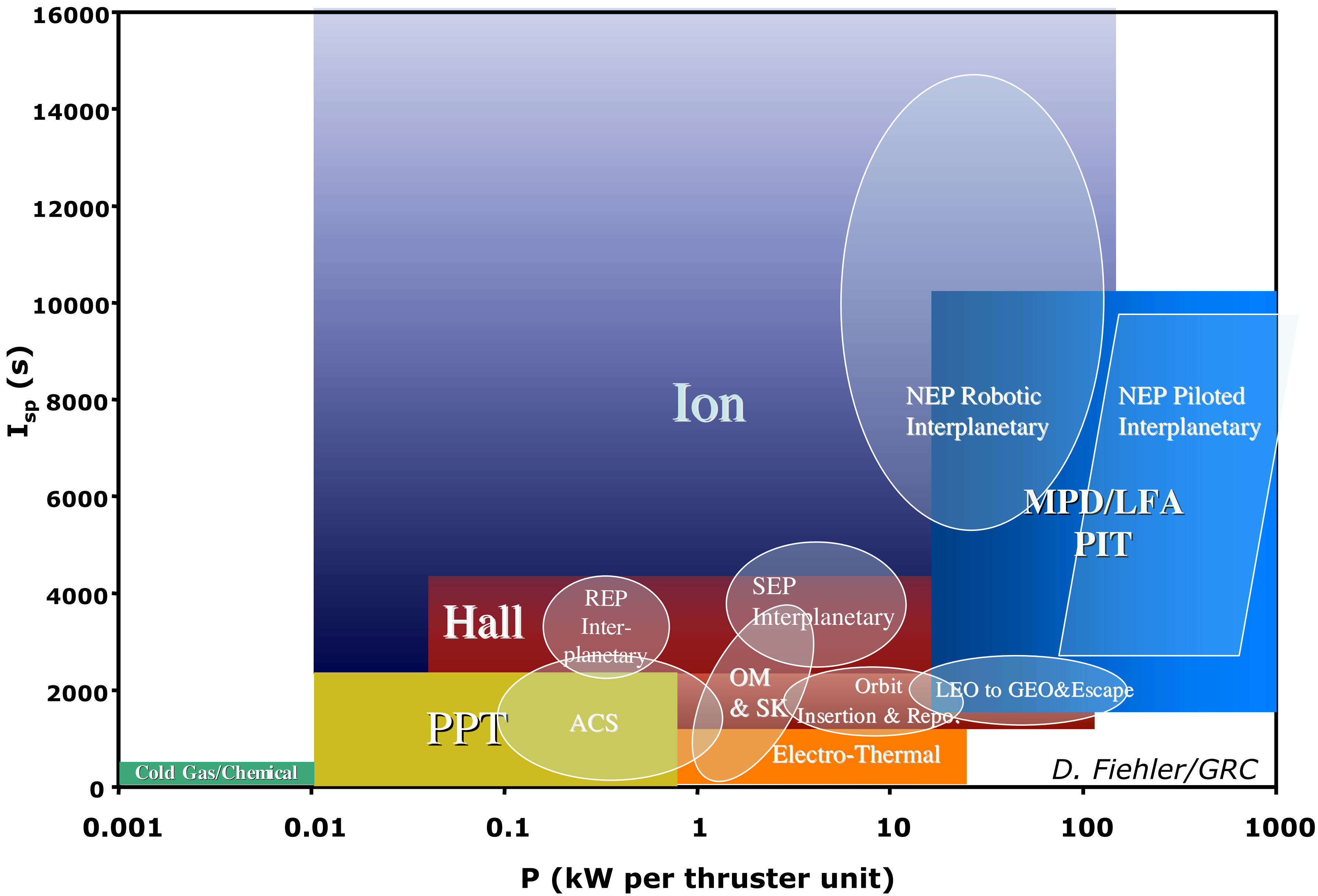




<u>Magnetoplasmadynamic</u> thrusters use a high power, steady-state current to ionize gas propellant, induce magnetic field (JxB)



Performance Regimes



In-Space Propulsion Technology Program: Solar Electric Propulsion Task Areas

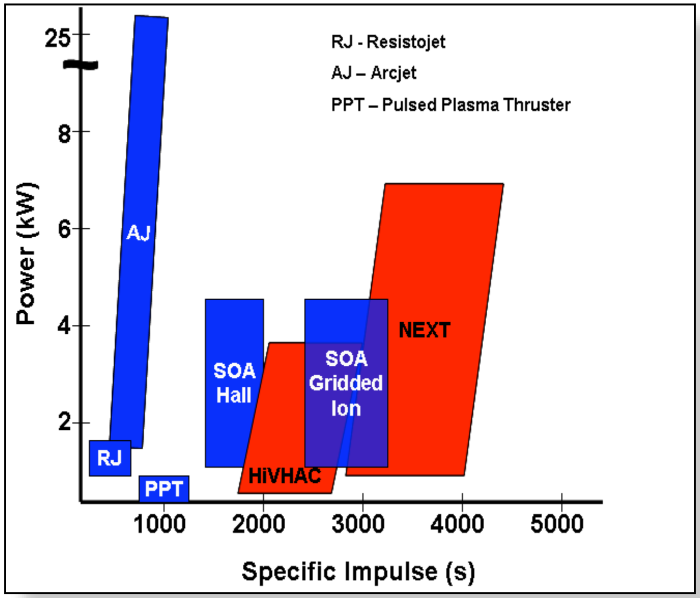
ISP SEP Task Areas

Primary SEP Tasks

- NEXT: NASA's Evolutionary Xenon Thruster
- HiVHAC: High Voltage Hall Accelerator
- Standardize thruster power and propellant flow systems to reduce costs

Objectives

- Expand the mission envelope of ion and hall thrusters
  - Extend thruster lifetime
  - Extend power range
  - Increase specific impulse
  - Expand SEP system capability to enhance or enable robotic earth and space science missions



J. Dankanich/MSFC

NEXT Ion Thruster

NASA's Evolutionary Xenon Thruster (NEXT)

- NSTAR 30-cm thruster flew on successful NASA Deep Space 1 mission, will be used on DAWN asteroid rendezvous mission (launch FY07)
- NEXT 40-cm thruster will expand SOA ion thruster capabilities to benefit Discovery/New Frontiers and other NASA science missions
  - Reduces number of thrusters required for demanding SMD science missions, reduces total system mass, improves thruster service life

Thruster Attribute	NSTAR[1]	NEXT
Max. Input Power, kW	**2.3**	**Up to 7**
Throttle Range	**4:1**	**Up to 10:1**
Max. Specific Impulse, s	**3,170**	**4,190**
Efficiency @ Full Power	**62%**	**71%**
Propellant Throughput, kg	**235**	**>300 (design)**
Specific Mass, kg/kW	**3.6**	**~2.5**

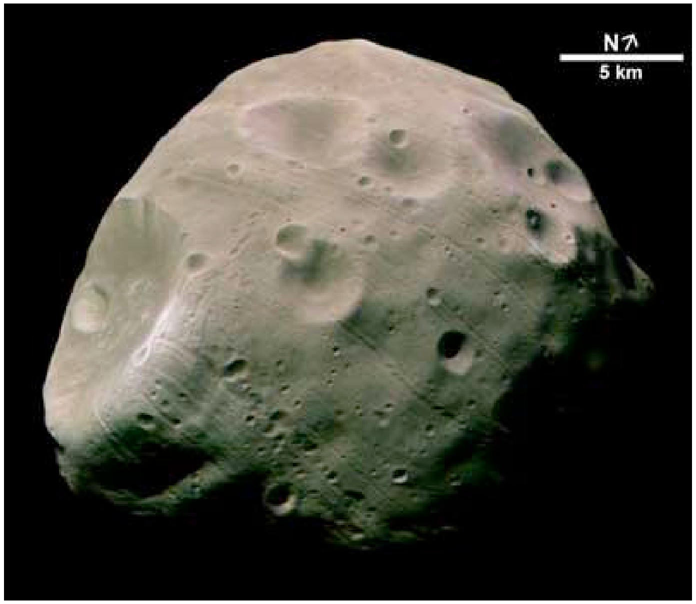
[1]NASA Solar Electric Propulsion Technology Application Readiness

NEXT Ion Thruster

Mission Applications

Configuration	Typical Mission	System Input Power Range	Thrust Range	Total Component Mass (excl. DCIUs)
1+1	Discovery	0.6 - 7.2 kW	25 - 236 mN	115 kg
2+1	Discovery, New Frontiers	0.6 - 14.4 kW	25 - 472 mN	172 kg
3+1	Flagship	0.6 - 21.6 kW	25 - 708 mN	229 kg

Discovery Mission Example: Sample Return from Deimos[1]



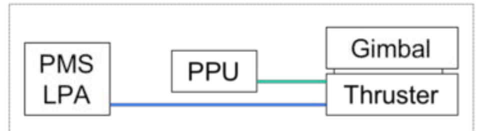
- NEXT SEP system
  - 1 operating thruster +1 spare
- Solar array power (1AU, BOL): 10-kW
- Launch Vehicle: Delta II-2925H
- Stay time: 90 days
- Total roundtrip transfer time: 2.91 years
- EP ΔV: 10.04 km/s
- Mass breakdown:
  - Launch mass: 1,065 kg (C3 =13.9 km2/s2)
  - Xenon propellant mass: 230 kg
  - Final mass: 835 kg

[1]D. Oh and K. Witzberger, 2005

NEXT Ion Thruster

Project Background

- Two-phase project to develop NEXT to TRL-5/-6
  - Sponsored by NASA Science Mission Directorate, conducted under MSFC In-Space Propulsion Technology Program
  - Implemented through competitive NRA
    - Phase 1: one-year base period, completed August 2003
    - Phase 2: multi-year (3+) option period, initiated October 2003
  - Addresses the entire ion propulsion system:
    - Thruster
    - Power processing unit (PPU)
    - Propellant management system (PMS)
    - System integration (including gimbal and control functions)



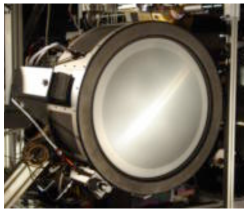
NEXT Thruster String

- <u>NEXT Project Team</u>:
  - NASA Glenn Research Center: Technology Project Lead
  - NASA Jet Propulsion Laboratory: System Integration Lead
  - Aerojet Corp: Thruster, PMS, DCIU simulators
  - L3 Comm ETI: Power processing unit
  - Participation by Applied Physics Lab, U. Michigan, Colorado State U.

NEXT Ion Thruster

Primary Hardware

- Five NEXT engineering model thrusters built
  - Four EM thrusters used in multi thruster array test
  - EM-3 undergoing long duration performance test (initiated 6/5/05)
    - Over 5500 hours of operation and 110-kg xenon propellant throughput; exceeds NSTAR Deep Space 1 flight experience
- One prototype (flight-like) model thruster built (PM-1)
  - Delivered by Aerojet to GRC in January 2006
  - Performance acceptance testing completed at GRC
  - Thruster shipped to JPL June 2006 for comprehensive testing
    - gimbal integration, random vibration, thermal vacuum tests

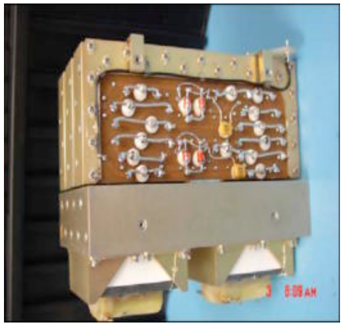


-Second prototype model thruster to be built in FY07 (PM-2)
  - PM-2 thruster life test planned at GRC in FY07
  - PM-1 remains available for operational testing

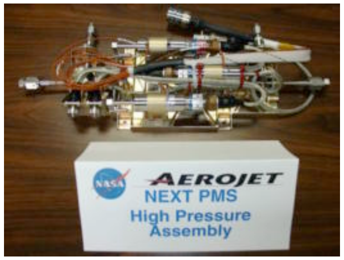
NEXT Ion Thruster

Primary Hardware, continued

- Power Processing Unit
  - Engineering model PPU in fabrication at L3 Comm ETI
  - Functional testing and delivery to GRC in August 2006
  - Operating characteristics:
    - Input power 0.62-kWe to 7.2-kWe
    - Main input power voltage 80-V to 160-V
    - Efficiency > 94% at peak power
    - Specific power > 0.2-kWe/kg



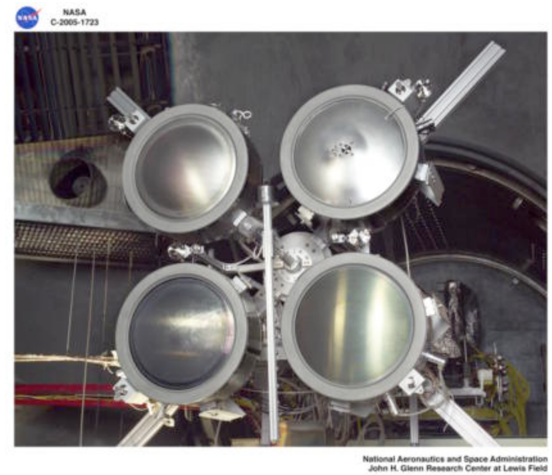
- Propellant Management System
  - All PMS assemblies complete
    - Two high pressure assemblies (one flight-like)
    - Three low pressure assemblies (one flight-like)
  - All assemblies have completed functional tests
  - Flight-like HPA and LPA have completed vibe tests, post-vibe functional tests

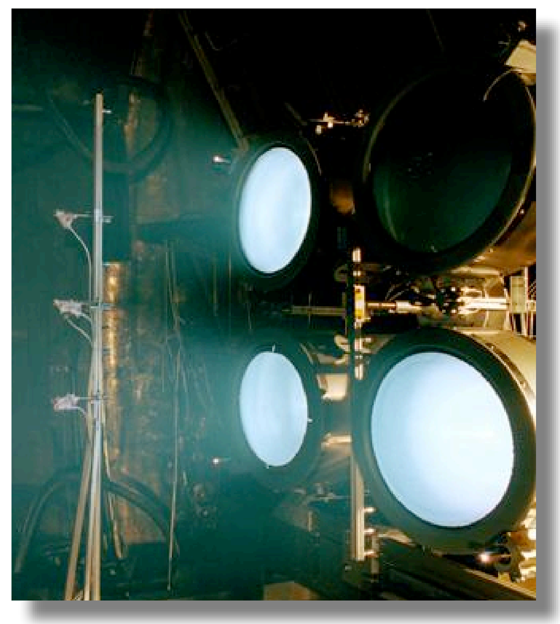


NEXT Ion Thruster

System Status

- Multi-Thruster Array Test (FY06)
  - Assess thruster and plasma interactions (effect of thruster spacing, gimbaled thrusters, neutralizer operating modes)
  - Four GRC EM thrusters (three operating, one instrumented non-operating)
  - Completed December 2005 at GRC
  - Expected performance achieved; well understood operations, no significant sensitivity to system configuration
- System Integration Test (FY07)
  - PM thruster, EM PPU, flight-like HPA and LPA, gimbal and DCIU simulator
- System Service Life Analysis (On-going)
  - Thruster life modeling and analysis





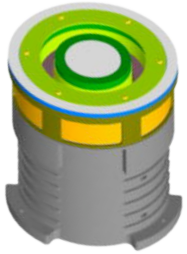
HiVHAC Hall Thruster

High Voltage Hall Accelerator (HiVHAC)

- Optimize Hall thrusters for NASA SMD missions
  - Operate at high voltage (~ 1000-V) to increase specific impulse
  - Operate at higher power density to increase thruster efficiency
  - Mitigate channel erosion to increase throughput and total impulse

- Primary HiVHAC Products:
  - SOA Design: NASA-94-M thruster with discharge channel walls thick enough to enable 150 kg of propellant throughput (GRC/Aerojet led design)
  - Advanced SOA Design: NASA-103M thruster with in-situ replacement of eroded channel walls to enable 300 kg of propellant throughput (GRC led design)
  - Numerical simulations of discharge channel erosion, validated with detailed experimental diagnostics using NASA-77M thruster (GRC, U. Michigan)

SOA



ASOA

HiVHAC Hall Thruster

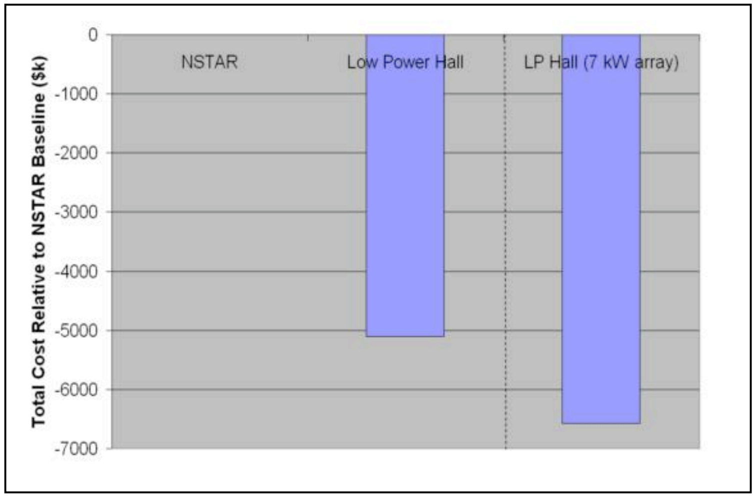
High Voltage Hall Accelerator (HiVHAC)

- Design Objectives:

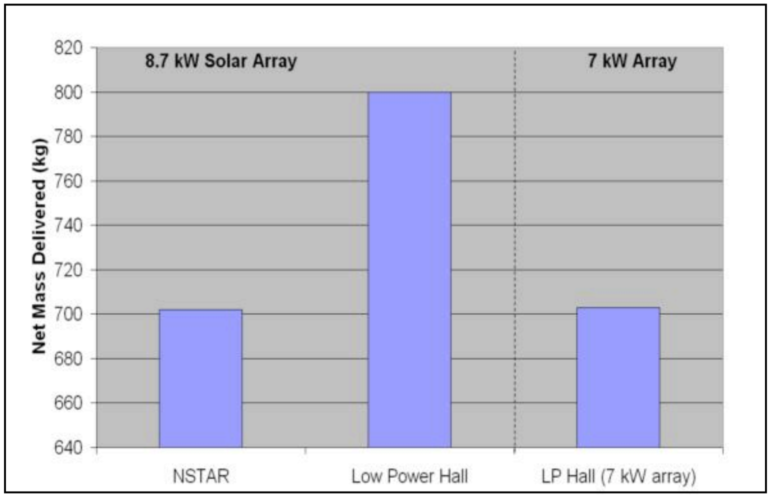
Input Power	0.3 – 3.6 kW
Specific Impulse	1600 – 2700 s
Efficiency	> 60%
Thrust	20 – 150 mN
Propellant Throughput	>150 kg (SOA) >300 kg (ASOA)
Specific Mass	1.3 kg / kW
Operational Life	> 10,000 hrs

Combined with lower system complexity, low power HiVHAC thrusters offer significant benefits for NASA Discovery missions

- Mission Example: DAWN cost and performance comparison



Reduced cost relative to NSTAR baseline

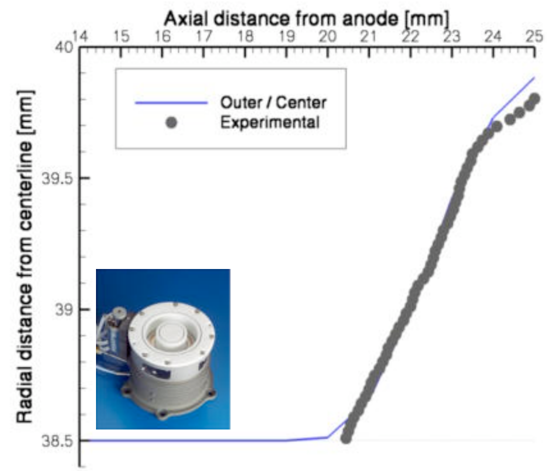


Increased payload relative to NSTAR baseline

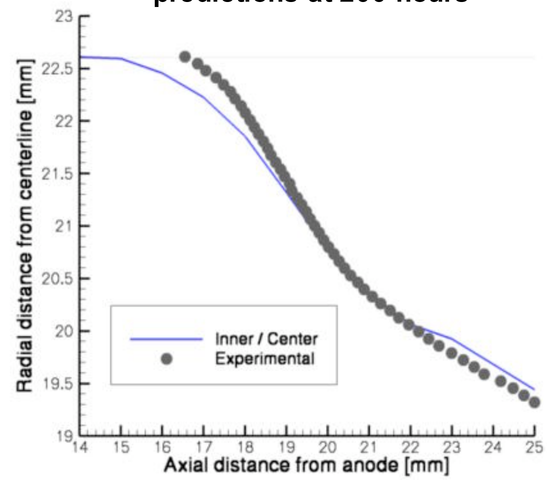
HiVHAC Hall Thruster

Erosion Simulations and Model Validation

- **Provide erosion data to validate hall thruster channel erosion models**
- **Erosion measured during wear test of NASA-77M thruster:**
  - 1.75-kWe (500 V, 3.5 A, 118 mA/cm^2)
  - Operated at lower power density to increase total operating time (limited by thruster wall thickness)
  - Wear profiles of inner and outer channel walls measured every 100 hours
  - Thruster performance measured continuously
- **Channel walls were significantly eroded after 300-hours of operation**
  - channel replaced and wear test continuing in order to gather additional erosion data



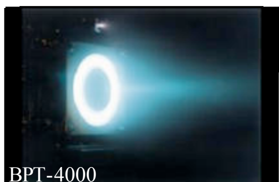
Erosion measurements and predictions at 200-hours



HiVHAC Hall Thruster

Additional Wear Testing with Aerojet BPT-4000 Thruster

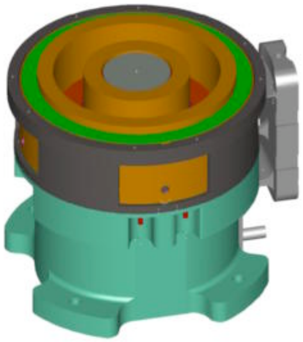
- BPT-4000 previously qualified by Aerojet with a 5600 hour life test
  - Lockheed-Martin/USAF customer
- NASA sponsored a 1000-hour life test extension (through June 2006)
- Additional wear data to improve fidelity of Hall thruster erosion models
- Depending on funding, Aerojet can extend life test to longer duration
  - Opportunity to evaluate use of commercial thrusters for NASA missions

 BPT-4000	Thrust (mN)		Specific Impulse (sec)	
	End of Life Test	Start of Life Test Extension	End of Life Test	Start of Life Test Extension
3.0 kW–300 V	**190**	**191**	**1839**	**1842**
3.0 kW–400 V	**171**	**172**	**2012**	**2008**
4.5 kW–300 V	**278**	**278**	**1963**	**1976**
4.5 kW–400 V	**254**	**256**	**2151**	**2162**

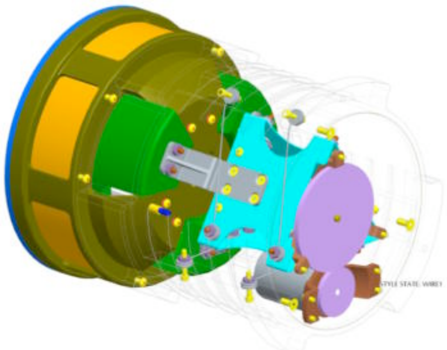
HiVHAC Hall Thruster

SOA and ASOA Thruster Status

- NASA-94M (SOA)
  - Aerojet fabrication of the State-of-Art (SOA) laboratory model thruster NASA-94M expected to be complete in late June 2006, followed by acceptance testing at GRC
- NASA-103M (ASAO)
  - Vendor fabrication of the Advanced State-of-Art (ASOA) laboratory model thruster NASA-103M expected to be complete by late July 2006, followed by acceptance testing at GRC
- Extended duration tests of SOA and ASOA thrusters planned for FY07



SOA

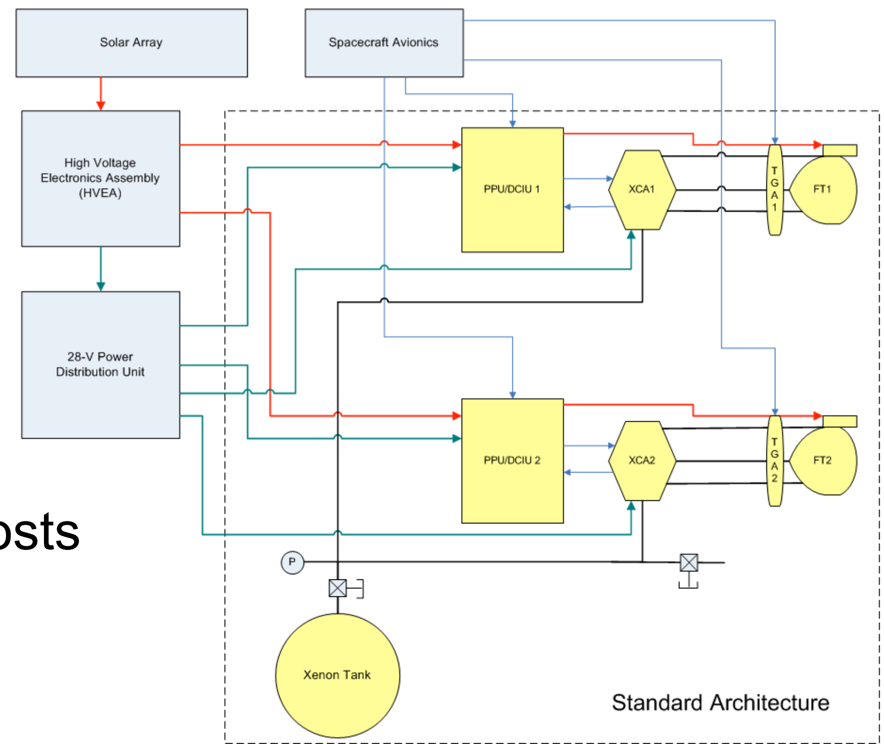


ASOA

Standard Architecture

<u>Objective</u>: reduce electric propulsion system non-recurring engineering costs by standardizing components and increasing manufacturability of sub-systems

- Single-string architecture to reduce system costs
- Operate various thrusters to match mission needs
  - NEXT, NSTAR, possibly commercial thrusters (XIPS)
- Standardize power supply topologies
- Embed DCIU to reduce production costs
- Standardize propellant management systems (LPA, HPA, VACCO, etc)



<u>Status</u>:

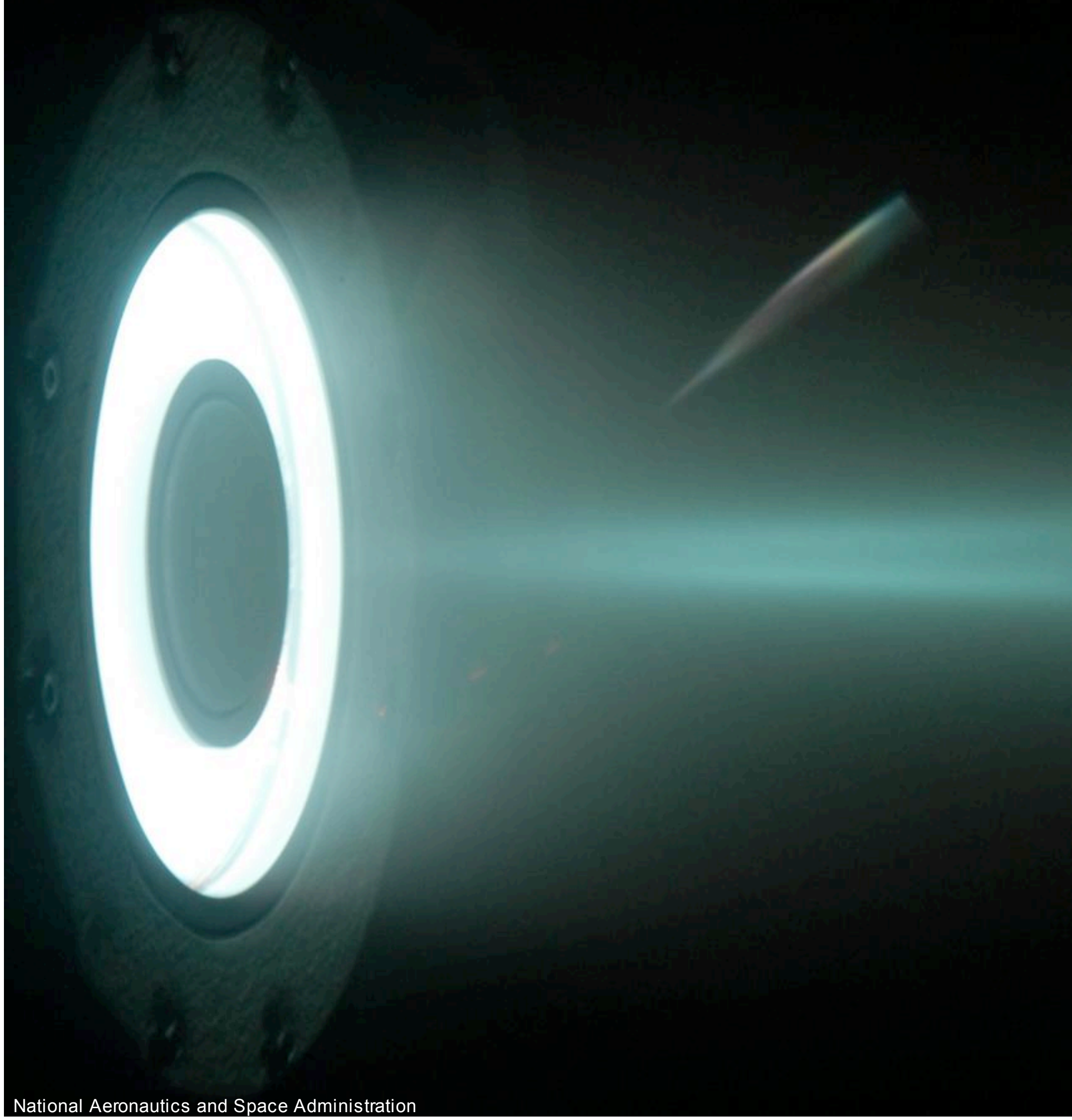
- PPU/DCIU design selection in FY06, initiate procurement in FY07

Proposed: Life Qualification Standards

<u>Objective</u>: improve method for thruster life qualification

- Thruster life qualification for SMD missions currently require several thousand to tens of thousands of hours of vacuum ground tests
  - Expensive and time consuming; roadblock to user acceptance
- Ongoing activities at NASA centers, industry, and universities to model ion and hall thruster erosion characteristics, predict thruster lifetimes
  - Ion grid erosion
  - Discharge cathode erosion
  - Hall thruster chamber erosion
- <u>Need to establish</u> a set of standards for electric propulsion thruster life qualification using combination of numerical models and limited ground test validation
  - Establish expert working group to develop standards, with SMD and TMCO participation (represent user community)
  - Identify, develop and validate remaining ion and hall thruster life models
  - Publish standards documents for community acceptance and use

For additional information on **Solar Electric Propulsion** within the In-Space Propulsion Technology Program, please contact:



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